INVESTIGATIONS OF HIGH-HARMONIC GYROTRONS WITH FREQUENCY-DOUBLED PREBUNCHED BEAMS*

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Abstract

There is currently considerable interest in operating gyrotrons at the second and higher cyclotron harmonics in order to access the near-THz regime and reduce magnetic field requirements. High frequency gyrotrons have successfully operated at the second harmonic [1]; however, competition from the fundamental harmonic limits operation and essentially precludes higher harmonic operation. Bandurkin and Savilov [2,3] recently proposed a scheme for frequency-doubled bunching of gyrating electron beams in a waveguide resonator formed from Bragg reflectors and with the drive frequency equal to the cyclotron frequency. Advantages of prebunching at twice the cyclotron frequency include suppression of the fundamental harmonic, enhanced second harmonic operation, and increased likelihood of fourth harmonic operation. We have investigated the use of this bunching technique to enhance higher-harmonic operation in gyrotron oscillators with annular beams. We compute the frequency-doubled bunching produced by a Bragg-type prebunching cavity and use a large-signal, multimode, multi-harmonic gyrotron oscillator code to simulate the effect of this bunching on a highly overmoded output cavity. Regimes of stable operation are predicted for second and fourth harmonic point designs.

I. INTRODUCTION

THz radiation, sometimes called T-rays, is currently of considerable interest for imaging hidden or obscured targets. Quite a large number of approaches have been proposed to use THz radiation for this application, but one thing they have in common is that they lack the power necessary to penetrate obscurants, overcome atmospheric attenuation, and achieve high scanning rates. The gyrotron oscillator can supply the necessary power while achieving the compactness and efficiency needed for vehicle use. Gyrotrons have achieved impressive powers at millimeter wavelengths but a performance breakthrough is needed before THz gyrotrons will be practical for DoD applications. A new effect called Frequency-Multiplied Phase Bunching (FMPB) can potentially achieve this breakthrough. Unlike gyroklystron bunching cavities, in which bunching occurs at the drive frequency, in this new class of gyro-device bunching occurs at a multiple of the drive frequency [2,3]. This suppresses fundamental harmonic interactions and increases the efficiency of higher harmonic modes. In this paper we investigate the frequency-doubled bunching case and use a large-signal, multimode simulation code to demonstrate enhanced second and fourth harmonic gyrotron operation based on FDBP.

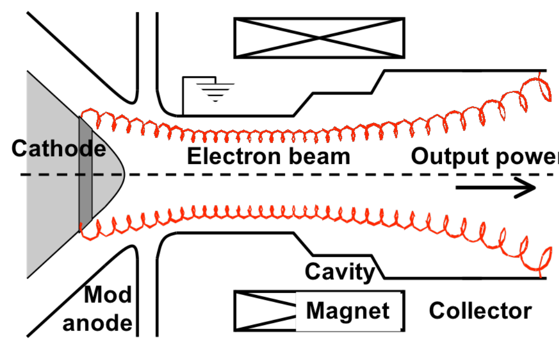

Figure 1. Schematic of a conventional single cavity gyromonotron. The cathode emits an electron beam which is accelerated through the interaction cavity which is situated in a magnetic field and toward the collector.

Gyrotrons operate at the cyclotron frequency or a harmonic thereof (28n GHz per Tesla where n is the harmonic number). The current state-of-the-art magnet technology does not extend above 21 T. In addition, magnet technology becomes more expensive with increasing fields above 10 T so it is not possible to build a CW gyrotron at 1 THz without using higher harmonics. In fact, a cost effective 1 THz gyrotron would need to operate in at least at the third harmonic, if not higher. Fig. 3 is a schematic of a conventional single cavity gyromonotron. The current highest-frequency gyro-devices use a single open cavity optimized for second harmonic operation. However, competition from first harmonic interactions increasingly limits harmonic

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14. ABSTRACT
There is currently considerable interest in operating gyrotrons at the second and higher cyclotron harmonics in order to access the near-THz regime and reduce magnetic field requirements. High frequency gyrotrons have successfully operated at the second harmonic [1]; however, competition from the fundamental harmonic limits operation and essentially precludes higher harmonic operation. Bandurkin and Savilov [2,3] recently proposed a scheme for frequency-doubled bunching of gyrating electron beams in a waveguide resonator formed from Bragg reflectors and with the drive frequency equal to the cyclotron frequency. Advantages of prebunching at twice the cyclotron frequency include suppression of the fundamental harmonic, enhanced second harmonic operation, and increased likelihood of fourth harmonic operation. We have investigated the use of this bunching technique to enhance higher-harmonic operation in gyrotron oscillators with annular beams. We compute the frequency-doubled bunching produced by a Bragg-type prebunching cavity and use a large-signal, multimode, multi-harmonic gyrotron oscillator code to simulate the effect of this bunching on a highly overmoded output cavity. Regimes of stable operation are predicted for second and fourth harmonic point designs.

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operation at higher frequencies and especially at higher harmonics such as the third harmonic. In addition, high oscillation start currents compared to the first harmonic and ohmic heating limit operation.

A gyrotron can operate at many frequencies by changing the magnetic field alone. In a 12 T magnet using a cavity with 2 mm radius and 1 mm beam radius, we can reach frequencies up to 335 GHz. By using the second harmonic, we can reach frequencies up to 670 GHz, however it is important to note that not all of these modes are accessible due to competition with the first harmonic modes. Over 1 THz can be achieved at 12 T in the third harmonic, and 1.3 THz at the fourth harmonic, however all third and fourth harmonic modes are presently inaccessible. We propose a new class of gyro-devices that will solve this problem and give us access to these higher frequencies and harmonics.

II. FREQUENCY MULTIPLIED PHASE BUNCHING

Conventional gyroklystrons bunch the beam at the drive frequency which is close to the fundamental harmonic. The bunched beam has higher harmonic content so that frequency multiplication can occur in the output cavity. However, the bunched beam also drives fundamental harmonic modes that increasingly compete with higher harmonic modes as the frequency and mode density increase. In the new bunching scheme, illustrated in Fig. 2, frequency-multiplied bunching occurs in the bunching cavity itself. This type of bunching all but eliminates competition from first harmonic modes and provides very effective pre-bunching for higher-harmonic modes. The external signal can be replaced with a self-excited pump gyrotron stage. The frequency multiplied bunching effect is based on the interaction with a periodic electric field. Consider an electron beam gyrating at the cyclotron frequency Ω_c in a periodic electric field $E_t(z) = E_t\,(z+\Delta L)$ of frequency $\omega = \Omega_c$. Expanding the field in a Fourier series:

$$E_t(z) = \sum_m A_m \exp(imhz) \qquad (1)$$

where $h = 2\pi/\Delta L$, it can be shown [2,3] that if the field has the form:

$$E_t(z) = A_{m_1} e^{im_1 hz} + A_{m_2} e^{-im_2 hz} \qquad (2)$$

phase bunching can occur at a frequency $n\omega$ where $n = m_1 + m_2$. Periodic field interactions are well known in microwave tubes and Free Electron Lasers but this one, which leads to bunching rather than energy exchange, does not appear to have been considered until very recently. These fields can be generated in a high-Q Bragg cavity such as shown in Fig. 3.

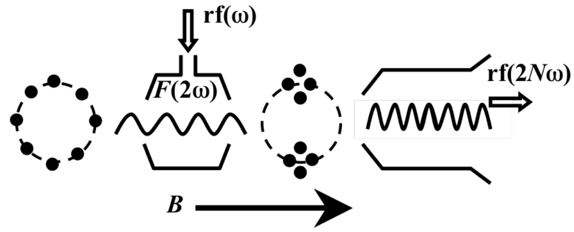

Figure 2. A new approach to enhanced high frequency harmonic operation: frequency-multiplied bunching.

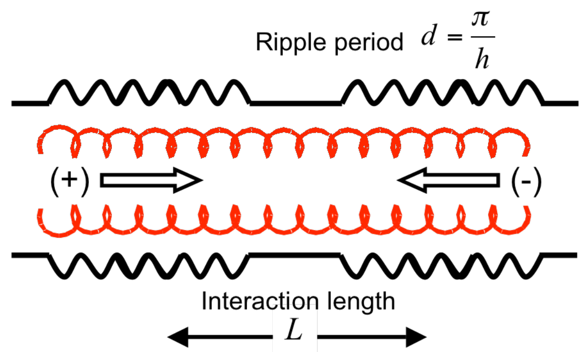

Figure 3. Hi-Q bunching cavity based on Bragg reflectors.

We have used the following equations-of-motion for a gyrating electron beam interacting with forward and backward propagating waveguide modes, such as can be found in a Bragg cavity, to investigate frequency-doubled bunching:

$$\frac{dw}{dZ} = -\beta_{\perp 0}\sqrt{1-\frac{2w}{\beta_{\perp 0}^2}}\left\{\begin{array}{l} A_1\cos\left[\phi_1 - (1-\frac{\Omega}{\omega})\frac{Z}{\beta_{\parallel 0}}\right] + \\ A_2\cos\left[\phi_2 - (1-\frac{\Omega}{\omega})\frac{Z}{\beta_{\parallel 0}}\right] \end{array}\right\}$$

$$\frac{d\phi_1}{dZ} = \frac{1-w}{\beta_{\perp 0}\sqrt{1-\frac{2w}{\beta_{\perp 0}^2}}}\left\{\begin{array}{l} A_1\sin\left[\phi_1 - (1-\frac{\Omega}{\omega})\frac{Z}{\beta_{\parallel 0}}\right] + \\ A_2\sin\left[\phi_2 - (1-\frac{\Omega}{\omega})\frac{Z}{\beta_{\parallel 0}}\right] \end{array}\right\} + \frac{\Omega w}{\beta_{\parallel 0}\omega} + \frac{hc}{\omega} \qquad (3)$$

$$\frac{d\phi_2}{dZ} = \frac{1-w}{\beta_{\perp 0}\sqrt{1-\frac{2w}{\beta_{\perp 0}^2}}}\left\{\begin{array}{l} A_1\sin\left[\phi_1 - (1-\frac{\Omega}{\omega})\frac{Z}{\beta_{\parallel 0}}\right] + \\ A_2\sin\left[\phi_2 - (1-\frac{\Omega}{\omega})\frac{Z}{\beta_{\parallel 0}}\right] \end{array}\right\} + \frac{\Omega w}{\beta_{\parallel 0}\omega} - \frac{hc}{\omega}$$

$$w = 1 - \frac{\gamma}{\gamma_0}, \quad \phi_1 = \phi + \frac{hc}{\omega}Z, \quad \phi_2 = \phi - \frac{hc}{\omega}Z$$

These equations describe the evolution of an electron's energy (w) and gyrophases relative to the forward (ϕ_1) and backward (ϕ_2) traveling waves in the Bragg cavity. The condition for frequency-doubled bunching is $\omega = \Omega_c$. This results in fast-time-scale interactions with the individual waves and a slow-time-scale interaction with the combination wave. The well-known cyclotron maser interaction and conventional phase bunching occurs when $\omega = \Omega_c \pm k_z v_z$. Unlike the cyclotron maser interaction, the FDPB condition does not involve velocity so the effect should be relatively insensitive to velocity spread.

Table I gives the parameters for a 300 GHz frequency-doubled bunching cavity simulated using the above equations. Figure 6 shows the simulation of frequency-doubled phase bunching. The figure shows the initial conditions at z=0 corresponding to uniformly distributed gyro-radii and phases for a single guiding center of an annular beam. The presence of a range of gyro-radii is caused by velocity spread. The bunched beam at the cavity output (z=L) is also shown. The presence of two bunching centers corresponds to frequency doubling. Fig. 5 shows the harmonic content of the bunched beam as a function of position in the bunching cavity. There is significant 4th-harmonic content in addition to 2nd harmonic. However, there is virtually no odd (1st or 3rd) harmonic content.

Table I. 0.3 THz Pre-Bunching Cavity Design

Waveguide mode	TE_{02}
Interaction length (L)	5 cm
Wall radius	2 mm
Phase velocity	1.2c
Circulating power	100 kW
Energy	20 keV
Gyro Pitch Ratio	1
Guiding center Radius	0.75 mm
Axial velocity spread	15%

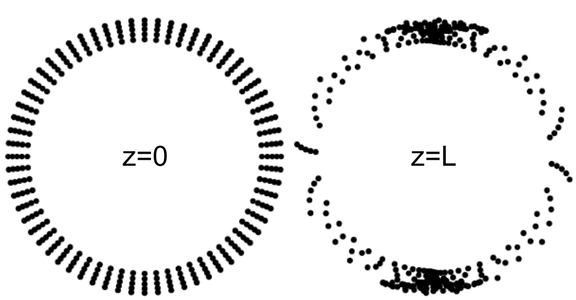

Figure 4. Simulation of frequency-doubled phase bunching, with the initial distribution of phases on the left and final distribution on the right.

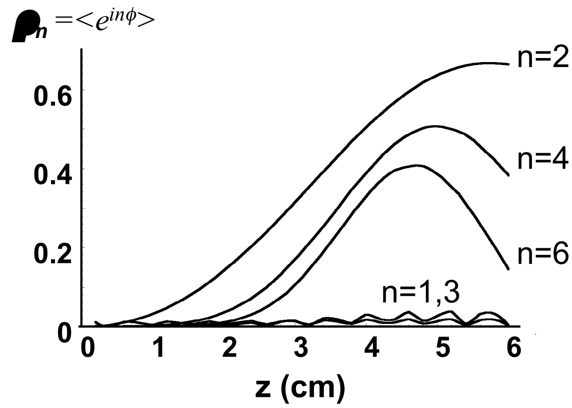

Figure 5. Simulation of frequency-doubled phase bunching showing the harmonic content of frequency-doubled bunched beam.

III. MULTIMODE SIMULATIONS

The effect of frequency doubled-bunching on harmonic gyrotron operation was modeled using a nonlinear, multi-mode computer code developed in previous research on gyrotrons and magnicons [4-6]. Multiple TE modes and harmonics can be included. The TE_{06} 2nd harmonic mode and the TE_{012} 4th harmonic mode are compatible with the TE_{02} FDPB cavity and were selected as possible operating modes. The simulation parameters are given in Table II. The most dangerous competing modes were identified from threshold current surveys and are shown in Figures 6c and 6d for the TE_{06} 2nd harmonic mode and TE_{012} 4th harmonic mode, respectively. The second and fourth harmonic simulation results showing output power and operating range are shown in Figures 8a and 8b.

Table II. Multimode parameters for simulation of a 2nd/4th harmonic, 0.6/1.2 THz gyrotron driven by a frequency-doubled bunched beam.

Beam voltage	20 kV
Beam current	0.5 A – 1A
Beam alpha	1 – 2
Beam radius	0.79 mm
Cavity radius	1.56 mm
Cavity length	1.5 cm
Q ($4\Omega_c$), Q ($2\Omega_c$), Q (Ω_c)	13000, 6000, 2000

The results show that FDPB enables efficient operation at much lower currents than possible for an unbunched beam. This simplifies electron gun and collector design and lowers ohmic losses as well as improving efficiency. Competition with fundamental harmonic modes has been practically eliminated. The 2nd harmonic calculations show 1600 W and 16% efficiency at 0.6 THz and the 4th harmonic design shows 120 W and 0.6% electronic efficiency at 1.2 THz. Note that the use of FMPB greatly enhances the efficiency as well as improving stability.

For example, the efficiency of the MIT 460 GHz 2nd harmonic experiment was less than 1%.

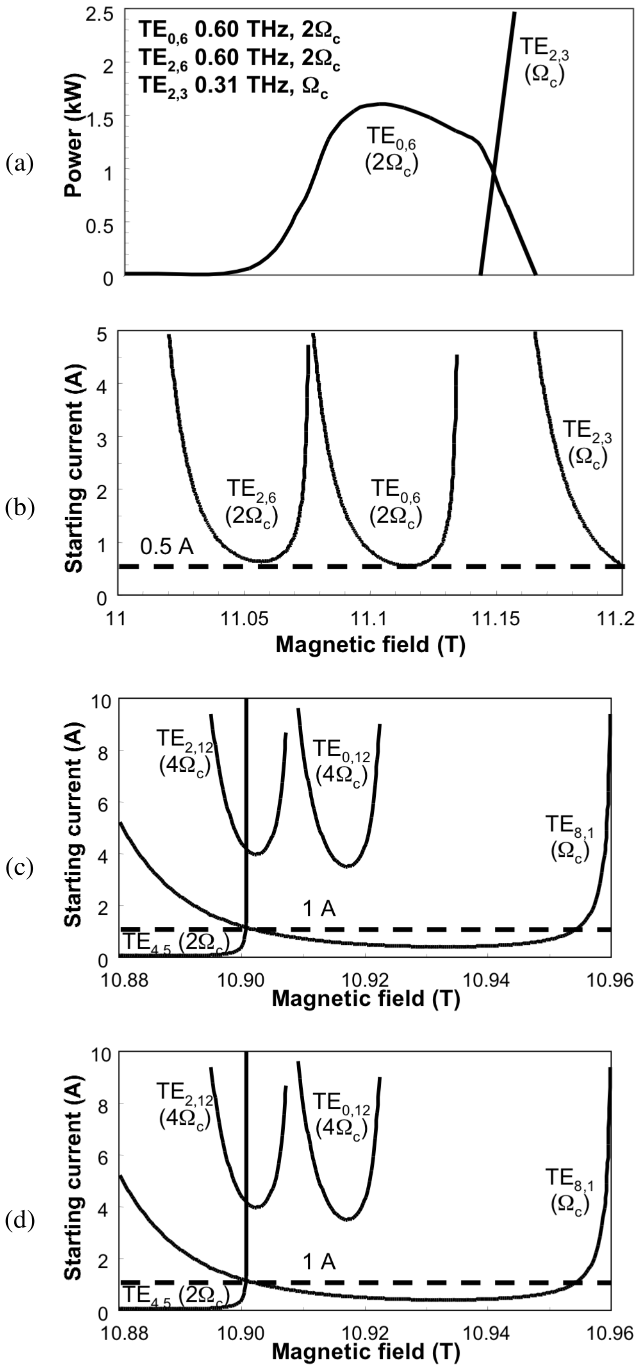

Figure 6. Simulation of a 2nd/4th harmonic, 0.6/1.2 THz gyrotron driven by a frequency-doubled bunched beam. (a) Second harmonic multimode simulation. (b) Its associated harmonic linear gyrotron theory. (c) Fourth harmonic multimode simulation. (d) Its associated harmonic linear gyrotron theory.

The drop in efficiency at the 4th harmonic, although still very high by THz source standards, is mainly caused by the decreased coupling strength at higher harmonics particularly at low voltages. That is, the rf fields needed to drive the 4th harmonic interaction to high efficiency would result in unacceptably high ohmic losses in the cavity. In fact, the above results for output power do not account for ohmic losses in the output cavity. When these are included, the output power for the second harmonic design drops to 1200 W, corresponding to 12% efficiency; and the output power for the fourth harmonic design drops to 50 W, corresponding to an efficiency of 0.25%.

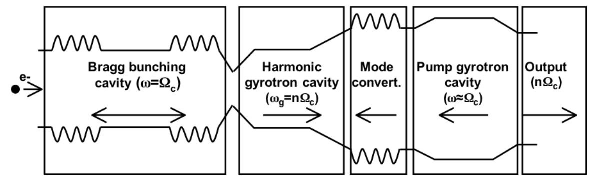

Figure 7. Conceptual multistage self-excited harmonic gyrotron with frequency-multiplied bunching.

In Figure 7 we show an example of a multistage self-excited harmonic gyrotron with frequency-multiplied bunching. A constant magnetic field is assumed to be present over the length of the device. The first event in the multi-stage sequence is that the pump gyrotron generates first harmonic radiation and the kilowatt level (and eliminating the need for an input drive source). Note that the first harmonic bunching occurs downstream in order to prevent contamination of the harmonic output. Next, the pump signal is converted to a mode suitable for the Bragg FDPB cavity. The pump signal then drives the Bragg bunching cavity producing circulating powers ~100 kW in the cavity. The Bragg cavity radius can be adjusted to minimize competing modes. Output power is then generated in the harmonic gyrotron cavity, which then exits the gyro-device at the right.

IV. SUMMARY

We have analyzed the effect of frequency-doubled phase bunching and its generation in a high-Q Bragg cavity. The calculations show that the frequency-doubled beam has considerable fourth harmonic content as well as second harmonic content, but virtually no first or third harmonic content. A beam with frequency-doubled bunching has been used as input to a nonlinear multimode computer code in order to investigate the impact of this type of beam on higher-harmonic operation in a gyromonotron. The simulations show that competition from lower-order harmonic interactions is greatly reduced for designs based on both second and fourth harmonic interactions. A conceptual design for second harmonic gyrotron with a self-excited frequency-doubled prebunching cavity has been included. Although incorporating a frequency-doubling pre-bunching cavity in a gyrotron device introduces a number of complications

to be discussed in future work, this does appear to be a promising approach to achieving stable operation at higher-harmonics.

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